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EVALUATION OF TANTALUM-TO-STAINLESS-STEEL TRANSITION JOINTS

by Adolph C. Spagnuolo

Lewis Research Center
Cleveland, Ohio

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SUMMARY

Tantalum-to-stainless-steel bimetallic transition joints were tested to determine the overall strength of the brazed joint. Tensile tests were conducted on flat sheet and tubular specimens at elevated temperatures 1350° F (1005° K) and vacuum levels of 10^{-7} to 10^{-6} torr (10^{-5} to 10^{-4} N/m^2). Studies were also conducted to determine if any unfavorable interdiffusion embrittlement was taking place between the braze material and the parent metals. A 2.5-inch (6.4×10^{-2}m) diameter by 0.125-inch (3.18×10^{-3} m) wall bimetallic joint was subjected to the temperature 1350° F (1005° K) and pressure 350 psia (2.41×10^6 N/m^2) levels expected in a liquid metal loop including 20 temperature cycles between 600° F (589° K) and 1350° F (1005° K).

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The tests indicated:

1. The parent material in all tensile specimens ruptured first, leaving the brazed area intact.

2. No significant interdiffusion occurred between the braze and the parent metals.

3. The 2.5-inch (6.4-cm) diameter tube remained leak tight after 150 hours of testing at 1350° F (1005° K) and 350 psia (2.41×10^6 N/m^2).

Ultimate and yield strength data are also included for unalloyed tantalum rods, plate and sheet test specimens at 1350° F (1005° K) at vacuum levels of 10^{-8} to 10^{-7} torr (10^{-6} to 10^{-5} N/m^2).

INTRODUCTION

High-strength transition joints of two dissimilar metals, for use at high temperatures, have been successfully manufactured in recent years. Combinations of materials such as those shown in table I are now commercially available. These joints permit the engineer to take advantage of the excellent corrosion and strength properties of the refractory and reactive metals in those areas where they are specifically needed within any assembly.

Refractory metal transition joints are especially applicable to liquid metal

systems where both high temperatures and very corrosive conditions are encountered. The mercury boiler used in a Rankine cycle power system represents one such problem area. Since mercury is highly corrosive, a study was undertaken to determine the material most compatible with mercury at elevated temperatures (ref. 1). Tantalum was observed to have the least solubility, as shown in figure 1, and was chosen as the mercury boiler material. Since tantalum-to-stainless-steel bimetal joints were not available, a program was initiated to manufacture and evaluate some of their physical properties for this particular combination.

This investigation was undertaken in order to evaluate the bimetallic joints. Tests were conducted at Rankine system operation conditions, including temperatures up to 1610° F (1150° K). The report includes an appendix by W. R. Young of General Electric that reviews the considerations given to the design of brazed bimetallic joints.

DESIGN CONSIDERATIONS

The tantalum-to-316-stainless-steel bimetallic tensile specimens were made with the tongue-in-groove configuration shown in figure 2. The higher tensile strength of the stainless steel dictated its selection for the tongue; having the smallest cross sectional area, the tongue is usually made from the stronger of the two materials being jointed.

The axial tensile strength of bimetal joints is dependent on the strength of the parent materials and the shear strength of the brazed area. Shear strength can be increased by simply increasing the length of the tongue and groove, L_1 and L_2 (fig. 2). By making L_1 and L_2 equal to the wall thickness $D1/2 - D2/2$ of the tube, the shear area for any given diameter will be twice the cross-sectional area of the tube, while a groove length of twice the wall thickness will increase the shear area by a factor of 4. Therefore, while the shear strength of the braze material is below the ultimate strength of the parent materials, a proper selection of L_1 and L_2 can produce a joint superior in strength to the parent materials:

Tongue and groove diameters are dictated by the brazing temperature and the differential expansion between the two parent materials. Since stainless steel expands at a greater rate than tantalum, the gap between D_3 and D_5 (fig. 2) must be large enough at room temperature to ensure a final gap of about 0.003 inch (8×10^{-5} m) on the radius to allow the braze to flow through the joint. Diameters D_4 and D_6 should be machined as close as practicable for assembly at room temperature.

A more detailed review of the considerations given to the design of brazed bimetallic joints is presented in the appendix.

TEST PROGRAM

The tantalum-to-316-stainless-steel bimetallic joint program consisted of a series of tests designed to determine the overall strength of the brazed joint.

Start

A number of test specimens, both flat sheet and tubular, were used for this purpose and are described in table II. The jointing of unalloyed tantalum to 316 stainless steel was accomplished by vacuum brazing at 2150° F (1449° K) with a brazing alloy (J-8400) consisting of 21 Cr-21Ni-8 Si-3.5W-0.4C-0.8B balance Co.

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The following tests were conducted to evaluate the brazed joints:

(1) Specimens of Configuration 1 (table II) were made of a flat sheet, 0.062-inch thick (1.58×10^{-3}m) tantalum-to-316-stainless steel joint (fig. 3) of the tongue-in-groove configuration. The joint was the first of its kind and therefore did not reflect the final joint geometry. Four tensile tests were conducted at 1350° F (1005° K) using a conventional vacuum testing machine at vacuum levels below 5×10^{-6} torr (7×10^{-4}N/m^2). Two specimens were tested as received and two were aged 116 hours in a vacuum furnace at 1350° F (1005° K). The specimens, during aging and tensile tests, were wrapped in tantalum foil to minimize contamination of the tantalum at elevated temperatures.

(2) Specimens of Configuration 2 were used for metallographic examination to determine whether any unfavorable interdiffusion embrittlement took place between the braze and the parent materials. Six specimens were machined from tantalum - 316-stainless steel plate brazed together with the tongue-in-groove design. Temperatures of 1350° F (1005° K), 1550° F (1116° K), 1750° F (1227° K), 1950° F (1338° K), and 2100° F (1422° K) were selected, and one specimen was aged in a vacuum furnace at each temperature for two hours. Each specimen was wrapped with three layers of 0.5 mil (1.3×10^{-4} m) tantalum foil.

Knoop hardness readings were taken across the specimens from the parent stainless steel, through the braze, and into the parent tantalum to determine the amount of embrittlement.

(3) Configuration 3 was a tube 2.5-inch (6.4×10^{-2} m) diameter by 0.125-inch (3.17×10^{-3} m) wall, tantalum-to-316-stainless steel, with a tongue-in-groove joint configuration. A tensile test was performed at 1350° F (1005° K) in an argon atmosphere at 760 torr (1.0×10^5 N/m^2). A thermal shroud surrounded the specimen and argon was circulated through the tubular joint to prevent contamination.

(4) Configuration 4 was a tube 2.5-inch (6.4×10^{-2} m) diameter, dimensionally the same as Specimen 3. The tantalum end was capped; the stainless steel end contained a 3/8-inch (9.5×10^{-3} m) diameter fill tube. The specimen was then placed in a vacuum furnace and subjected to an internal helium pressure of 350 psia (2.4×10^6 N/m^2) at 1350° F (1005° K). Twenty thermal cycles between 1350° F (1005° K) and 600° F (589° K) were performed during the 150-hour test with vacuum levels in the low 10^{-7} torr (10^{-5} N/m^2) range.

(5) Configurations 5 and 6 were two tubes 0.75-inch (1.90×10^{-2} m) diameter by 0.080-inch (2.03×10^{-3} m) wall, tantalum-to-316-stainless steel joints, of different designs. One joint was brazed and employed the tongue-in-groove

configuration (fig. 4(a)) while the second, Configuration 6, was a co-extruded design (fig. 5(a)) without braze. Tensile tests were conducted on each specimen at 1350° F (1005° K) in a vacuum chamber.

(6) Tensile specimens of unalloyed tantalum were machined from 0.75-inch (1.90×10^{-2}-m) rod, Configuration 7; 1-inch (2.5×10^{-2}-m) and 0.25-inch (6.3×10^{-3}-m) plate, Configuration 8; and 0.156-inch (3.98×10^{-3}-m) sheet, Configuration 9. Tensile tests were conducted in a conventional vacuum testing machine at levels of 10^{-6} to 10^{-7} torr (10^{-4} to 10^{-5} N/m^2) with specimen temperature at 450° F (505° K) and 1350° F (1005° K). Tantalum foil, 0.5 mil (1.3×10^{-4} m) thick, surrounded the specimens for the entire gage length during testing.

RESULTS AND DISCUSSION

Configuration 1 - Tensile Specimens (Table II)

Flat sheet tensile specimens were made to determine the strength of the brazed joint. The specimens should fail at the root of the stainless-steel tongue since the cross-sectional area of the stainless steel is one-third that of the tantalum and the ultimate strength of the tantalum is approximately one-half that of the stainless steel at 1350° F (1005° K). The rupture stress of 316 stainless steel was taken as 44 000 psi (1.7×10^8 N/m^2) at 1350° K (ref. 2).

The results of the tests are presented in figure 6. The bimetallic joint rupture stress was based on the rupture load and the original cross sectional area of the tongue before brazing. This value is seen to be higher than the rupture stress of the stainless steel tongue. Because of braze spillage during the brazing operation which increased the effective cross sectional area of the tongue, the actual strength of the joint was increased.

Specimens 1a, 1b, and 1c failed in the stainless-steel tongue as shown in figure 7. Specimen 1d failed in the tantalum material indicating the most braze spillage. The parent material in all four specimens failed leaving the brazed area intact. The design and ultimate strength of this type transition joint will therefore be determined by the physical properties of the parent materials.

Configuration 2 - Metallographic Studies

Metallographic examinations were made to observe the possible formation of intermediate phases at the base metal-brazing alloy interface. Specimens were prepared according to part (2) of the test program. Microstructures of the specimens are shown in figures 8(a) to 8(c) and the Knoop hardness readings, taken across the specimens from the parent stainless steel to the parent tantalum, are graphically represented in figure 9.

The interface between the stainless steel and the braze was chosen as the reference plane. Distances measured from the reference plane into the stainless steel are plotted to the left while those from the reference plane into the braze

and tantalum are plotted to the right. The distance across the braze is not constant. This can be attributed to machining tolerances and thermal expansion between the tongue and groove during the braze cycle. The variation in braze thickness is also shown in figure 9. The braze/tantalum interface varies from 3 mils (0.7×10^{-4} m) in some samples all the way to 6.5 mils (1.6×10^{-4} m) in others.

The hardness readings remained fairly constant in the stainless steel at a Knoop value of 200 with a slight hardness increase of the stainless steel due to some intergranular diffusion near the braze area. On the other side, the tantalum has hardened the braze by diffusion into the braze as indicated by higher hardness reading in the braze area near the tantalum parent material. The hardness readings in the tantalum remained constant at a Knoop value of about 180 as shown in figure 9.

Configurations 3 and 4 - 2.5-inch (6.4×10^{-2} m)

Tensile Specimen 3. - A tensile test was conducted on a 2.5-inch (6.4×10^{-2} m) diameter tantalum-to-stainless-steel bimetal tube. The two materials were brazed together using the tongue-in-groove joint configuration shown in figure 10. Voids in the early bimetal joints with some braze spillage are shown in figure 10(a). Improved brazing techniques eliminated these voids (fig. 10(b)) and increased the effective cross-sectional area of the tongue.

The root of the stainless-steel tongue was assumed to be the plane of rupture. The calculated failure load of the tongue was determined to be 13100 pounds (2.7×10^4 N) based on an ultimate tensile stress of 44000 psi (1.7×10^8 N/m^2) in the stainless steel at 1350° F (1005° K). When the specimen reached 1350° F (1005° K) the load was applied and failure occurred at 15600 pounds (6.9×10^4 N). The difference between calculated and actual rupture load was due to braze spillage around the circumference of the stainless steel tongue, thereby increasing its area.

The yield point of the tantalum was reached as evidenced by the elongation and necking-down shown in figure 11. As brazing techniques are improved, the voids (fig. 10(a)) at the stainless steel tongue should disappear, thereby increasing the cross-sectional area at the root of the tongue to nearly that of the tantalum. With this increase in area, the failure should now occur in the tantalum tube since its ultimate tensile stress is only approximately one-half that of stainless steel at 1350° F (1005° K).

Pressure-temperature (test specimen 4). - In order to use tantalum bimetal joints in liquid metal loops, an investigation was made to determine if any leaks occurred at the brazement during thermal cycling with an internal pressure. The test specimen was prepared according to section (4) of the test program and shown in figure 12.

Inside the vacuum chamber the specimen was evacuated with a mechanical roughing pump and filled with helium three times to minimize contamination

from the internal air trapped in the specimen.

The bimetal capsule was then heated to 1350° F (1005° K) and subjected to a hoop stress of 3500 psi (2.4×10^7 N/m^2) and an axial stress of 1750 psi (1.2×10^7 N/m^2) by pressurizing it with helium to 350 psia (2.4×10^6 N/m^2). Twenty thermal cycles were conducted in a vacuum furnace from 1350° F (1005° K) to 600° F (589° K) with an average heating thermal gradient of 53° F per minute (284° K/min) and an average cooling thermal gradient of 16° F per minute (264° K/min). At the end of 150 hours the vacuum level of the chamber was 1.7×10^{-7} torr (2.21×10^{-5} N/m^2) indicating no leaks in the tube.

Further testing beyond the 1350° F (1005° K) temperature level and 350 psia (2.4×10^6 N/m^2) pressure level was then conducted. The temperature of the specimen was increased to 1610° F (1150° K) while maintaining a constant 350 psia (2.4×10^6 N/m^2) internal pressure. The temperature was then lowered and held constant at 1350° F (1005° K) while the pressure was increased to 575 psi (3.9×10^6 N/m^2) resulting in a hoop stress of 5750 psi (3.9×10^7 N/m^2). The increased values of temperature and pressure exceed the design values by 20 and 64 percent, respectively.

The bimetal capsule remained leak tight in all of the above cases. Visual inspection made after removing the capsule from the chamber showed no evidence of cracks in the braze.

Configuration 5 and 6 - Tubular Tensile Specimens

Two bimetal tubes, 0.750 inch (1.9×10^{-2} m) diameter were tested in tension at 1350° F (1005° K) in a conventional hydraulic testing machine. One tube employed the brazed tongue-in-groove design shown in figure 4(a). The second tube, Specimen 6, consisted of an extruded design shown in figure 5(a).

Both specimens failed in the tantalum tube as expected. The rupture stress was slightly higher in the tongue-in-groove (fig. 4(b)) tube, 23 600 psi (1.6×10^8 N/m^2) as compared to 21600 psi (1.5×10^8 N/m^2) for the extruded tube (fig. 5(b)).

The increased effective cross-sectional area of the stainless-steel tongue due to improved brazing techniques resulted in the tantalum failure as predicted. Predictions on the ultimate strength between the two specimens should not be made on the basis of these two tests alone. Only after a series of tests using several sizes of bimetal joints can a true comparison be made.

Configurations 7, 8, and 9 - Tantalum Tensile Test

It was observed early in the program that design data on the ultimate and yield strength of tantalum at 450° F (505° K) and 1350° F (1005° K) would be

difficult to obtain from the present literature due to excessive scattering. Data found in references 3 to 7 are plotted in composite form in figures 13 and 14. A large amount of scattering is observed throughout the temperature ranges. It became immediately apparent from this data that to design with tantalum, data must be obtained from the actual material that is to be used.

Tensile specimens were machined and the test conducted according to section (6) of the test program. The results of these tests are presented in table III and plotted in figures 13 and 14. Although Specimens 1, 2, and 3 were tested at the same temperature (1350° F; 1005° K) and in a vacuum, the results were different for each thickness, the ultimate stress for the 1-inch thick specimen being 30 percent high then for the specimen 1/2-inch thick. Specimen 4 tested at 450° F (505° K) had higher strength levels as expected due to the lower test temperature.

The proper selection of tantalum is therefore very important. Factors to look for which influence the strength of tantalum are: methods of production, amount of contamination, amount of cold working, recrystallization, and grain size. Cold-working wrought tantalum increases the tensile strength by a factor of 2 (ref. 3) over recrystallized material. Additions of nitrogen, oxygen, or carbon also increase the tensile strength of tantalum considerably (refs. 3 and 5). Finer grain size tantalum materials will generally show slightly better tensile strengths (ref. 5).

CONCLUDING REMARKS

Tantalum-to-stainless-steel bimetallic joints and unalloyed tantalum tensile specimen were tested at 1350° F (1005° K) in a vacuum chamber.

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The following observations were made:

1. All the joints failed in the parent material, either the tantalum or the stainless steel, leaving the brazed area intact.

2. Eliminating voids at the root of the tongue [in a tongue and groove joint] increased the ultimate strength of the joint because of the increased effective cross-sectional area of the tongue.

3. No unfavorable interdiffusion occurred between the J-8400 braze and either parent material.

4. The tantalum material must be carefully selected, and it is recommended that before fabrication, tensile tests at design operating temperature be made on the actual tantalum material to be used in the assembly.

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Lewis Research Center,

National Aeronautics and Space Administration,

Cleveland, Ohio, December 6, 1967,

701-04-00-02-22.

APPENDIX - BRAZED BIMETALLIC JOINTS

by W. R. Young*

General Considerations

Tubular transition joints between the refractory metals, columbium, tantalum, molybdenum, and tungsten, their alloys, and the more conventional structural materials such as stainless steels and the nickel or cobalt base superalloys present two basic problem areas. First, the equilibrium matallurgical interactions will result in the formation of intermetallic phases with very low ductilities, generally well below those of the parent metals. Second, the coefficient of expansions of the components will differ by a considerable factor, such that differential expansion is about 6 to 9×10^{-6} inches per inch °F. It is the function then of joint design to best accommodate these two factors and produce a joint which will maintain useful strength and integrity during extended elevated temperature service. This service temperature is preferably equivalent to that of the nonrefractory metal being joined. It is the purpose here to discuss the brazed bimetallic joint solution to these problems and to provide some insight into the brazing process.

Two basic bimetallic joint designs are shown in figure 15 along with a schematic of critical joint dimensions. It should be noted that placement of braze fillets on the nonrefractory metal member is generally preferred for both type joints because the braze coefficient of expansion more closely matches that member. Otherwise, the joint types are simple reversals of each member, and this provides design versatility which will be described later.

The brazing process itself dictates several of the critical dimensions as illustrated in figure 15. For example, the difference between outside diameters (D_2 - D_7) is maintained at 0.040 to 0.050 inch to provide for placement of the braze alloy and braze fillet formation. The brazing operation is conducted at 2150° F. At this temperature the brazing alloy flows from the outside diameter, around the tongue, forming an effective double shear joint for axial loads. To provide a 0.002 to 0.005-inch gap for capillary braze alloy flow at the brazing temperature, D_3 and D_6 are sized using the simple differential expansion equation:

$$\Delta D = D \Delta T(\alpha_2 - \alpha_1)$$

where:

ΔD	change in diametral clearance, in.
D	joint diameter, in.
ΔT	temperature change to brazing temperature, °F
$\alpha_2 - \alpha_1$	difference in mean coefficient of thermal expansion, in./in./°F

Thus, for a 1.0 inch diameter joint, brazed at 2150° F, with a typical $\alpha_2 - \alpha_1 = 6 \times 10^{-6}$ in./in./° F:

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*General Electric Co. - Cincinnati, Ohio, Space Power and Propulsion Section.

$$\Delta D = (1)\,(2080)\,(6\times10^{-6}) = 0.012\text{-inch}$$

If a braze gap of 0.003 inch is desired, then $D_3 - D_6 = \Delta D + 2(0.003) =$ 0.018 inch (fig. 15). It is apparent that for the Type B joint this gap is reversed such that the gap is maintained between D_5 and D_4. Referring again to the Type A joint, D_4 and D_5 are made to the closest fit possible in machining since the differential expansion produces braze clearance in this area at the brazing temperature.

From the differential expansion equation it is apparent that diametral clearance increases with joint diameter. This places a practical restriction on the diameter of the joint which can be brazed effectively since the braze must flow through the joint by capillary attraction. Although it has not been determined experimentally, ΔD values near 0.040 inch, representing joints near 4 inches in diameter, would approach this practical limit. This limitation might be overcome by using tapered sections which would allow axial movement at the brazing temperature, thus effectively decreasing the braze gap; however, this procedure has not been verified experimentally.

In many applications, D_1 and D_8 are identical to prevent flow restrictions at the joint area. If this is not a design requirement, however, D_8 may be about 0.020 inch larger than D_1 to provide a braze fillet similar to the outside diameter.

The axial tensile strength of the brazed joint is determined by the braze shear strength and the tensile strength of the joint components. By increasing length L_1, L_2 (fig. 15), the shear strength of the braze becomes secondary because the shear area may be increased to many times the cross-sectional area of the joint components. For example, a typical braze alloy (J-8400 cobalt base) has a shear strength of 13000 psi at 1500° F, compared to a yield strength of 35000 psi for (Haynes 25) L-605. For any size joint, a groove depth equal to the wall thickness would provide a shear area double that of the tube cross section. By further increasing groove depth to twice the wall thickness, failure would occur in the L-605 member since a fourfold increase in braze strength would be attained.

To be conservative, it may be assumed that the braze alloy possesses no strength under pure tensile stress. If the braze shear area is sufficient to induce failure of the parent metal, such failure would generally occur at the base of the tongue where the cross-sectional area is smallest. Again, considerable design latitude is possible. The component having the tongue may be made from the stronger of the two alloys being joined, and its cross-sectional area can be increased to some extent. Generally, by proper balancing of design variables it is possible to induce failure in either joint member, and each combination must be considered individually.

Upon cooling to room temperature after brazing, the brazed joint is subjected to differential expansion stresses which will exceed the yield strength of the joint materials. These stresses are strain induced, and therefore can be

relieved by small amounts of plastic deformation. Because the braze alloy and intermetallic compounds formed during service are brittle, compressive loading of the braze area is preferred. It is apparent that for either type joint, one side of the brazed joint is in compression and the other probably has tensile loading. This situation is reversed upon heating of the joint, to a degree depending upon the amount of plastic deformation which occurred previously. Experimentally, joints produced between ductile materials such as Cb-1Zr alloy and type 316 stainless steel have exhibited negligible deformation after 125 thermal cycles between 500° and 1600° F. No experimental limits have thus been established for either thermal cycling or strength capability of these joints.

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TABLE I. - COMBINATIONS OF BIMETALLIC TRANSITION JOINTS COMMERCIALLY AVAILABLE

Stainless steel (300 series)	Zircaloy Zirconium Titanium Ti-6 Al-4 V Ti-$5\frac{1}{2}$ Al-$2\frac{1}{2}$ Sn Columbium Cb-1 Zr Cb-5 Ti
Stainless steel (400 series)	Zircaloy

TABLE II. - SPECIMEN SIZE AND TEST CONDITIONS OF TANTALUM-316 STAINLESS STEEL JOINTS AND UNALLOYED TANTALUM MATERIAL

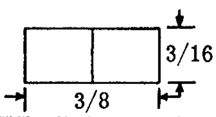
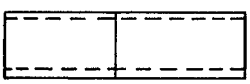
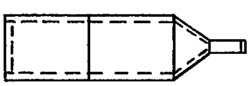
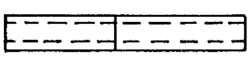
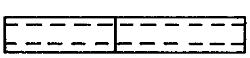
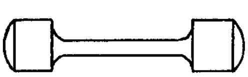
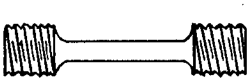
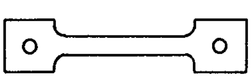
Configuration of specimens	Size	Material	Test	Test temperature, ^{o}F	Pressure, torr
1 	$\frac{1}{16}$-in. thick flat sheet	Tantalum-316 stainless steel joint	Tension	As received and 1350	10^{-6}
2 	$\frac{1}{16}$-in. thick flat sheet	Tantalum-316 stainless steel joint	Metallographic examination	1350, 1550, 1750, 1950, and 2100	10^{-6}
3 	$2\frac{1}{2}$-in. diam tube	Tantalum-316 stainless steel joint	Tension	1350	760
4 	$2\frac{1}{2}$-in. diam tube	Tantalum-316 stainless steel joint	Pressure and Temperature	600 to 1350	10^{-6} (outside) 350 psia (inside)
5 	$\frac{3}{4}$-in. diam tube	Tantalum-316 stainless steel joint	Tension	1350	10^{-6}
6 	$\frac{3}{4}$-in. diam tube	Tantalum-316 stainless steel joint	Tension	1350	10^{-6}
7 	0.160-in. diam	Tantalum	Tension	450	10^{-7}
8 	0.160-in. diam	Tantalum	Tension	1350	10^{-7}
9 	0.156-in. thick sheet	Tantalum	Tension	1350	10^{-7}

TABLE III. - TENSILE PROPERTIES OF UNALLOYED TANTALUM

Specimen	Temperature		Vacuum,[a] torr, $\times 10^{-6}$	Ultimate tensile strength, 1000 psi	Yield strength, 1000 psi, 0.2 percent offset	Elongation, percent	Reduction of area (R.A.), percent	Condition of tantalum as received
	°C	°F						
1	732	1350	1.0	17.3	7.0	56	93	ASTM grain size 6
5/32-in. sheet			1.8	17.3	6.6	52	95	Spinning grade-deep draw
			1.1	17.5	5.9	61	92	
			1.3	17.5	6.6	56	88	
			1.0	17.6	7.6	51	95	
			1.0	18.1	8.7	55	91	
2	732	1350	0.98	15.5	6.2	64	90	Fully annealed
1/4-in. plate			2.0	15.9	5.3	62	79	Element Max. wt % Min. wt %
			2.6	16.0	5.0	44	79	Tantalum ----- 99.9
			.94	16.3	5.0	61	85	Carbon 0.010 ----
			2.1	16.8	7.7	52	73	Oxygen .010 ----
			2.4	17.5	5.0	59	84	Nitrogen .010 ----
								Hydrogen .010 ----
3	732	1350	5.0	18.0	10.7	32	81	Annealed-grain size 5
1-in. plate			1.0	21.0	9.0	41	84	Product chemistry, ppm
			2.6	21.2	8.5	37	83	Carbon 20
			3.4	21.7	9.6	44	84	Nitrogen 5
			2.0	22.8	9.7	32	82	Oxygen 90
			1.0	23.4	9.3	40	79	Hydrogen 3.3
4	232	450	(b)	29.0	10.6	69	100	ASTM grain size 7
3/4-in. diam rod	232	450	(b)	28.8	11.1	69	100	Product chemistry, ppm
	232	450	(b)	28.0	10.2	66	100	Carbon 40
								Nitrogen 22
								Oxygen 100
								Hydrogen 3.6

[a] Vacuum measured at test temperature.

[b] Vacuum level at test temperature 10^{-5} torr.

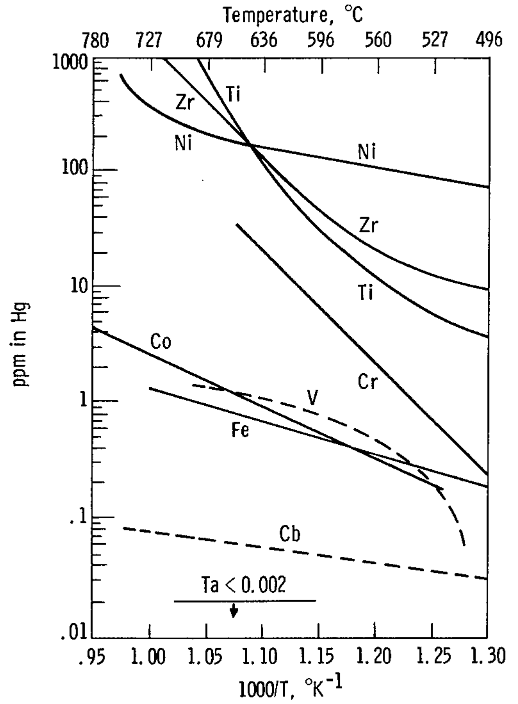


Figure 1. - Liquidus curves of metals in high temperature mercury.

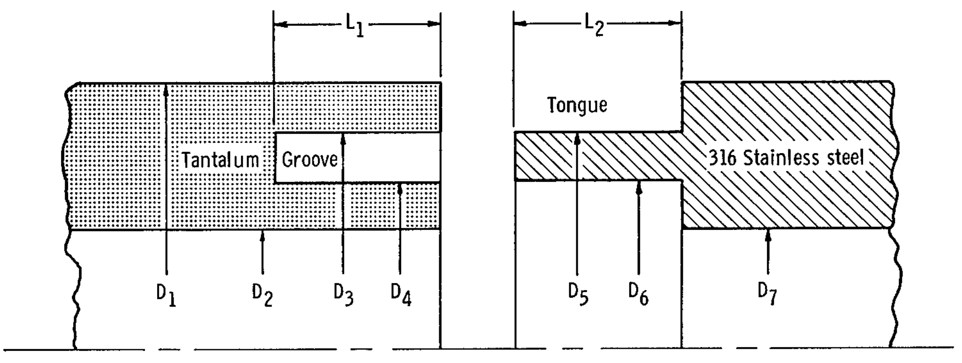


Figure 2. - Bimetallic tongue-in-groove joint schematic.

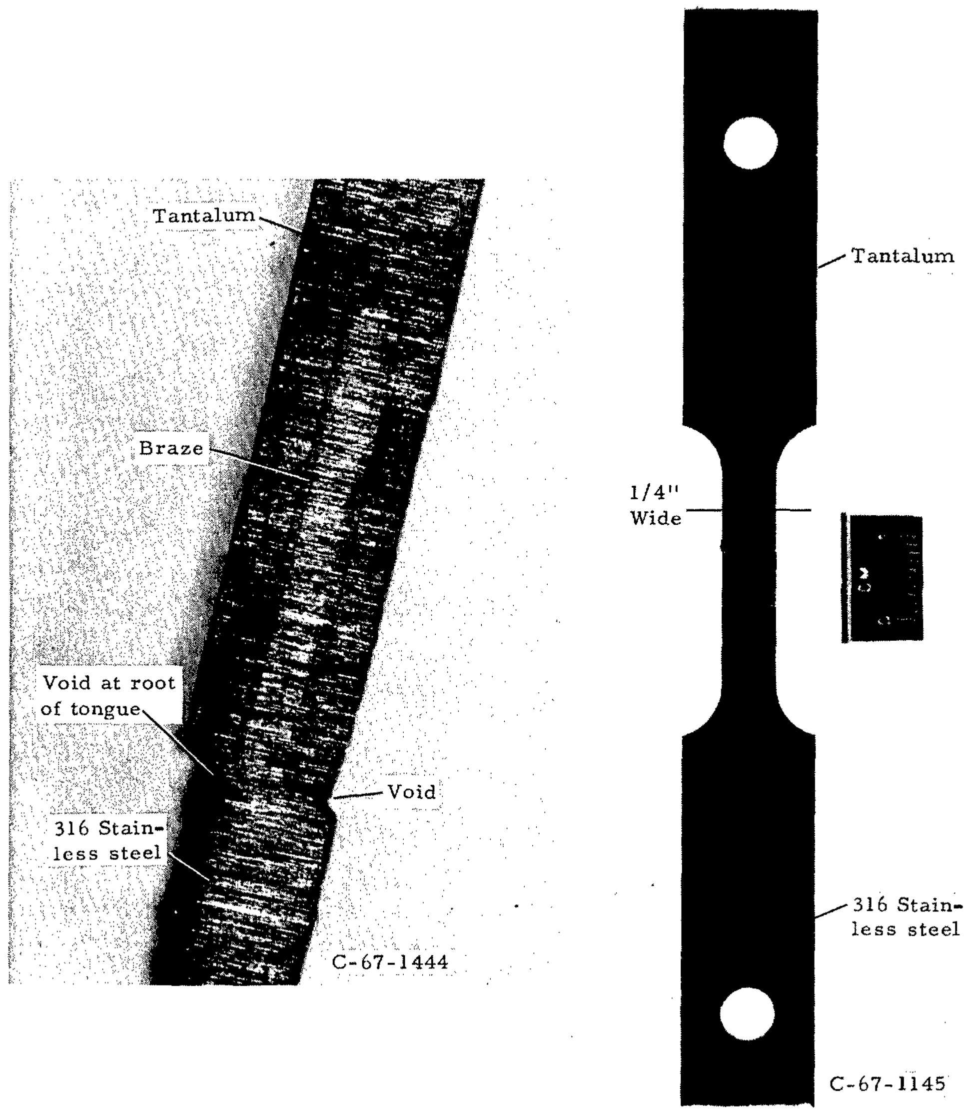
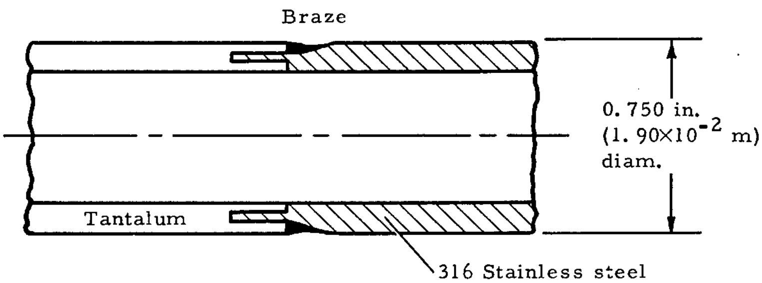
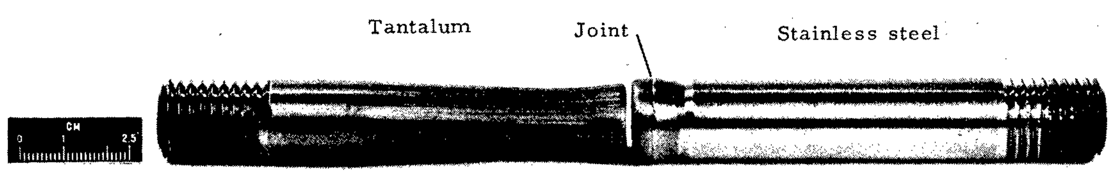


Figure 3. - Tensile specimen number 1. Flat sheet bimetallic joint.



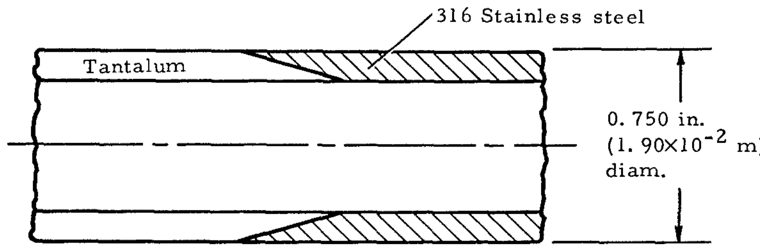
(a) Cross section.



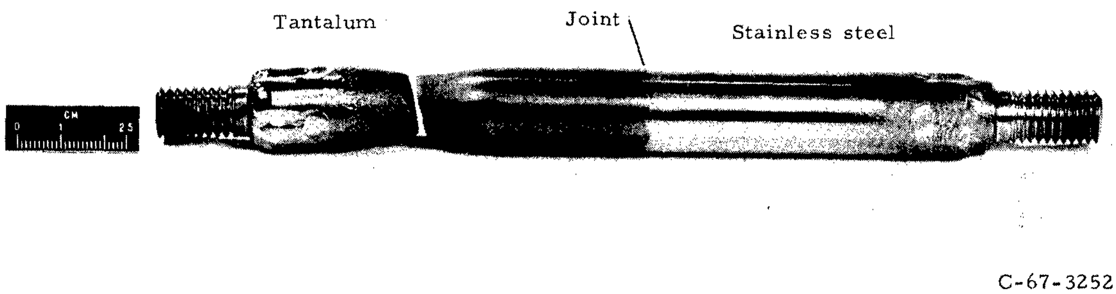
C-67-3253

(b) Tensile specimen after test.

Figure 4. - Tongue-in-groove joint. Tantalum to 316 stainless steel.



(a) Cross section.



(b) Tensile specimen after test.

Figure 5. - Extruded joint. Tantalum to 316 stainless steel.

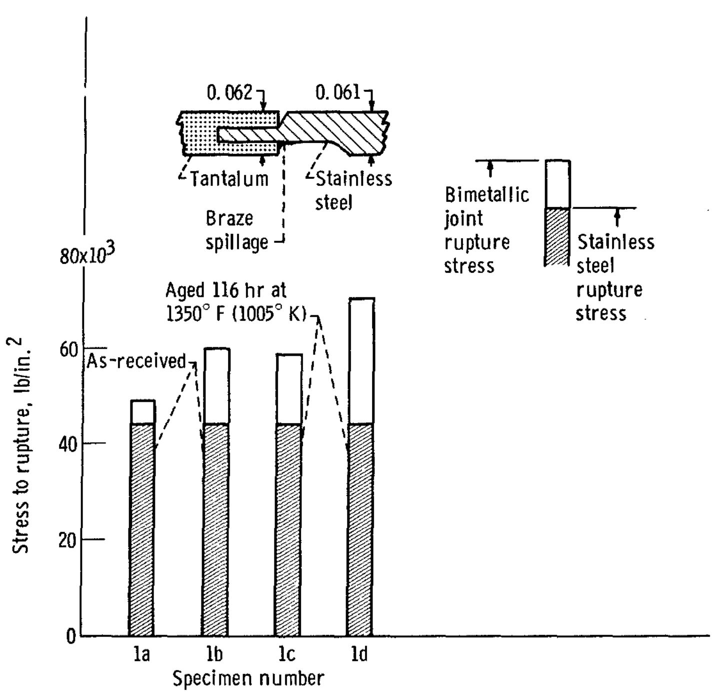
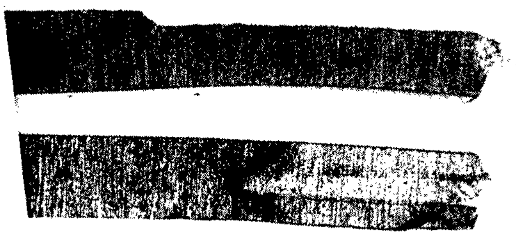
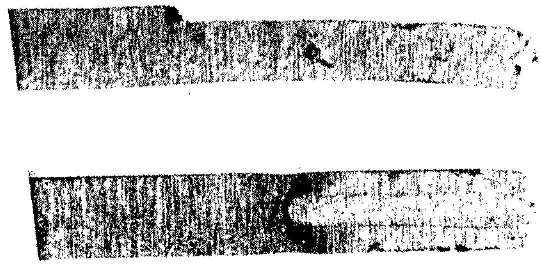


Figure 6. - Rupture stress of Ta/316 SS bimetallic joint.



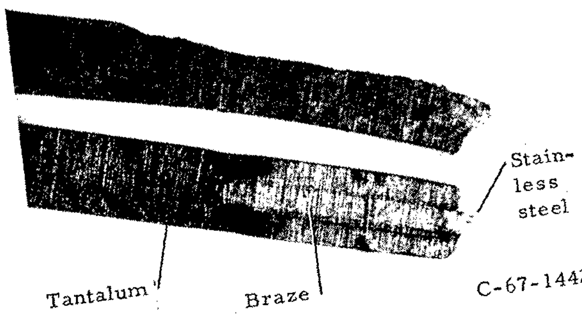
C-67-1440

Specimen number 1a. As received. (10×)



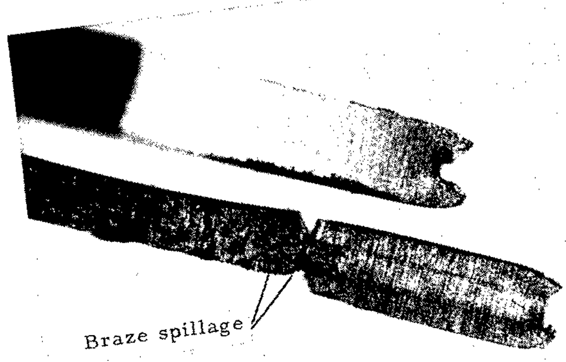
C-67-1441

Specimen number 1b. As received. (10×)



C-67-1442

Specimen number 1c. Aged 116 hours at 1350° F. (10×)



C-67-1443

Specimen number 1d. Aged 116 hours at 1350° F. (10×)

Figure 7. - Photograph of tensile specimens broken at 1350° F.

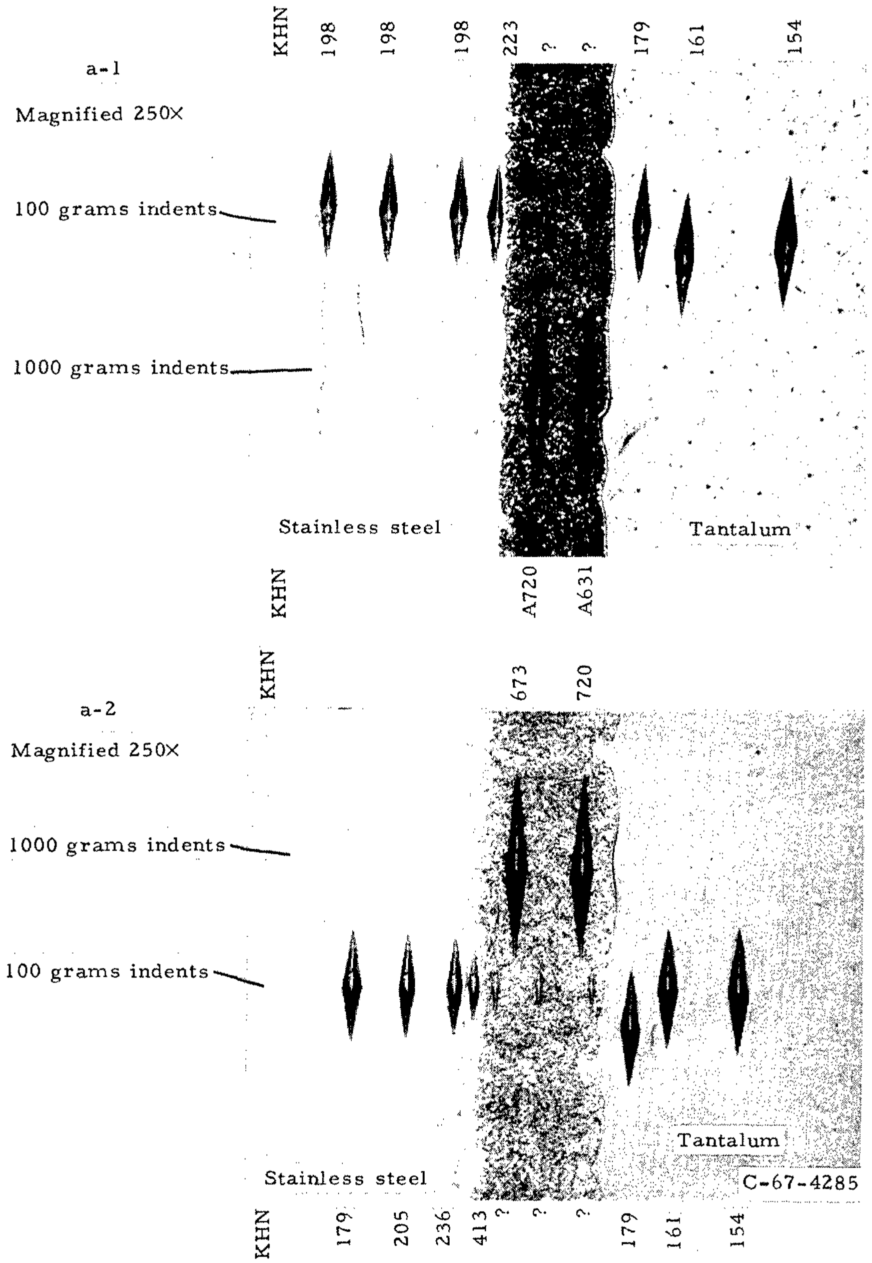


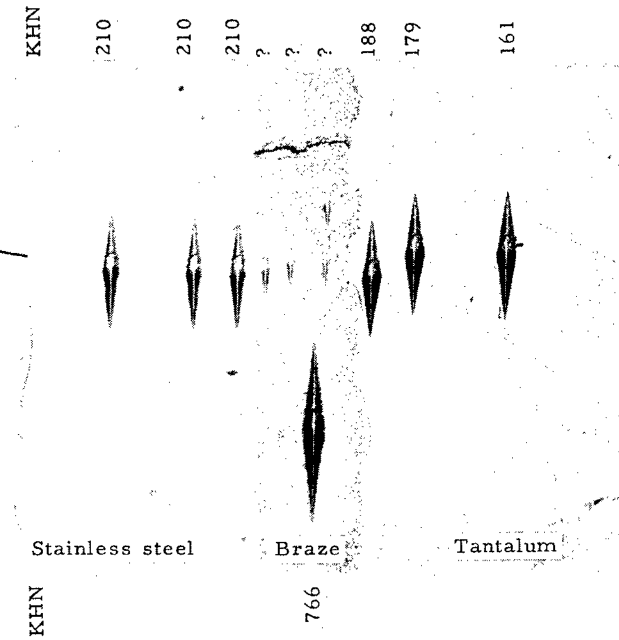
Figure 8(a). - Microstructure of Ta/316 S. S. transition joint after two hour aging at various temperature.

b-1

Magnified 250X

100 grams indents

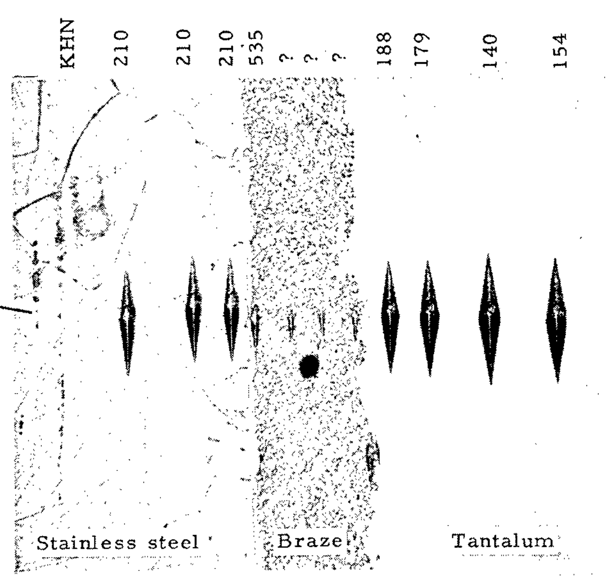
1000 grams indent



b-2

Magnified 250X

100 grams indents



C-67-4286

Figure 8. - Continued.

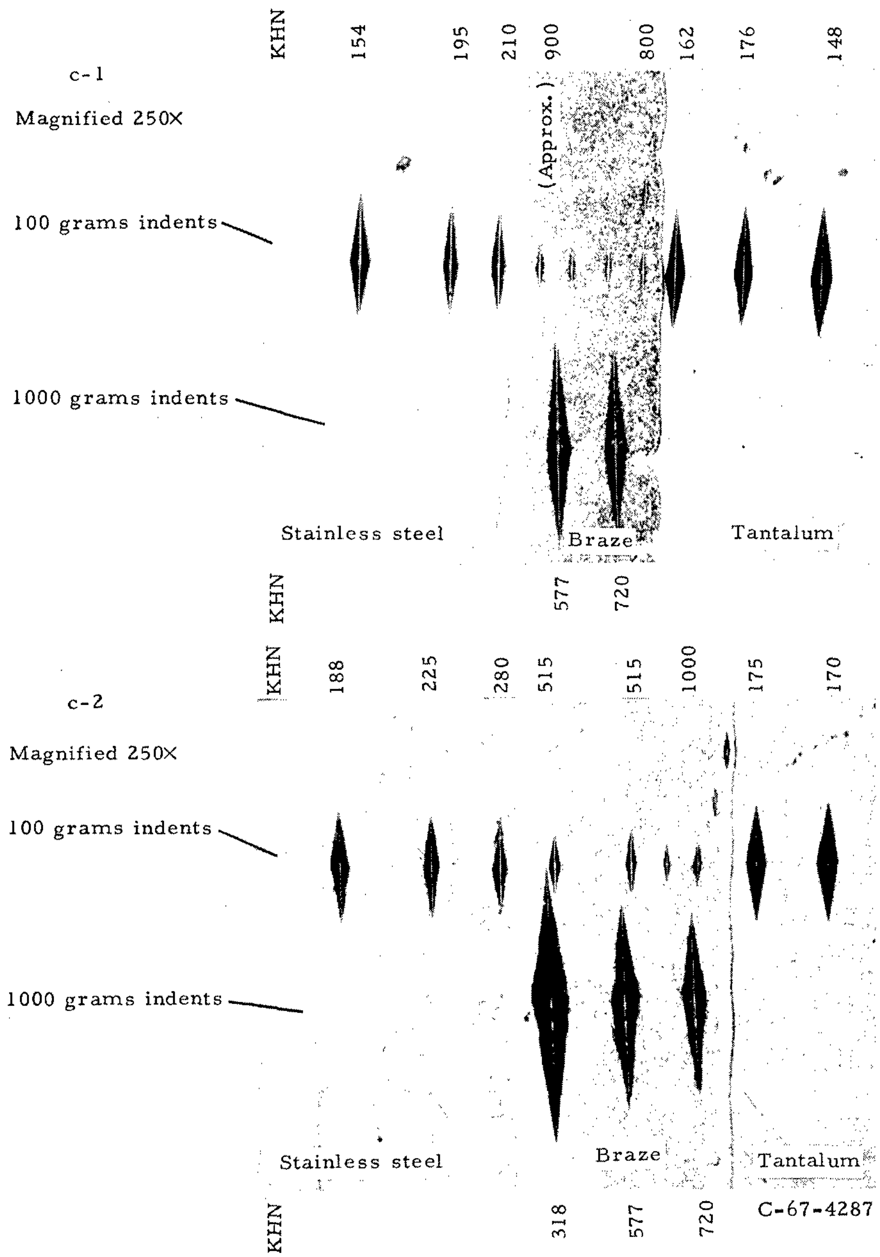


Figure 8. - Concluded.

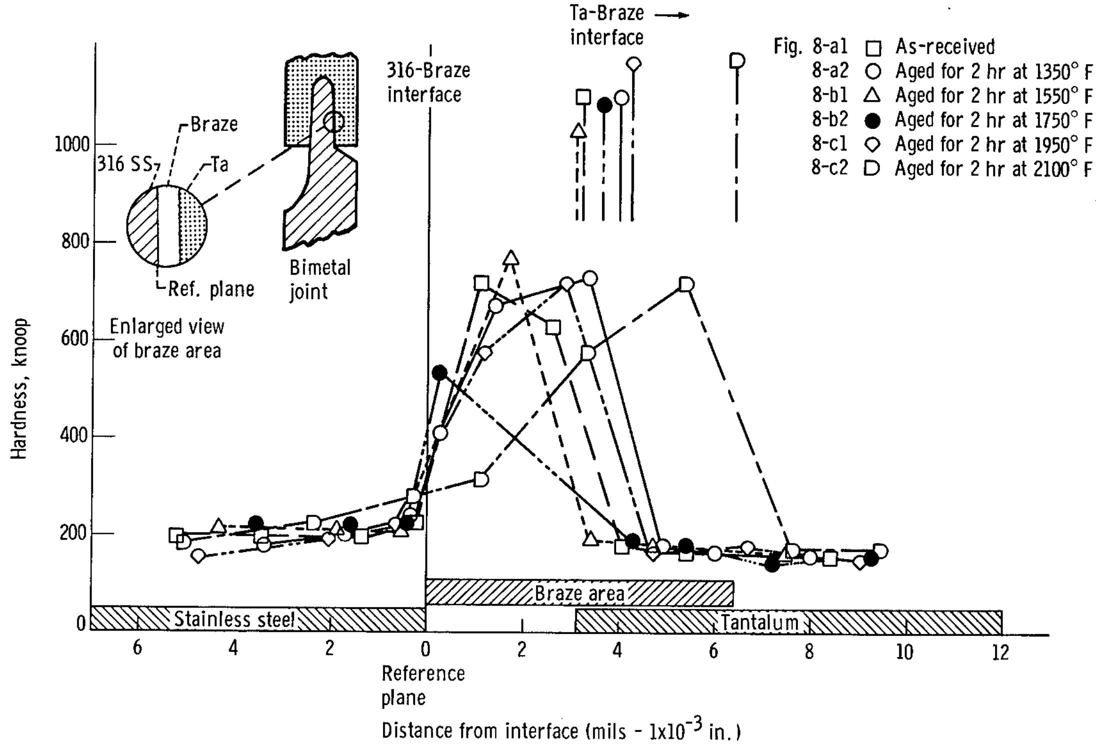
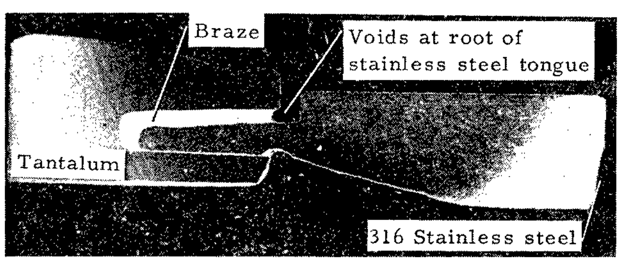
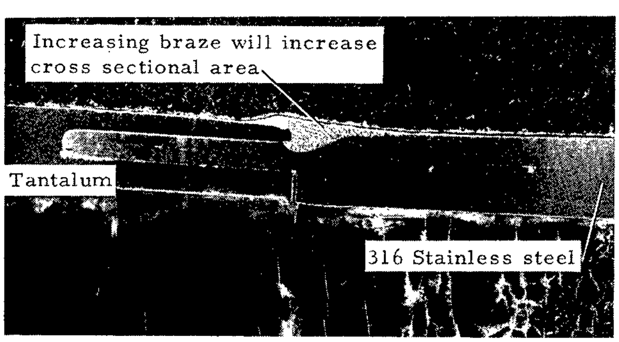


Figure 9. - Hardness traverse across brazed joints.



(a) 2.5 Inch diameter joint showing voids at root of stainless steel tongue.



C-67-4288

(b) 0.75 Inch diameter joint showing improved brazing technique.

Figure 10. - Tongue-in-groove joint configuration.

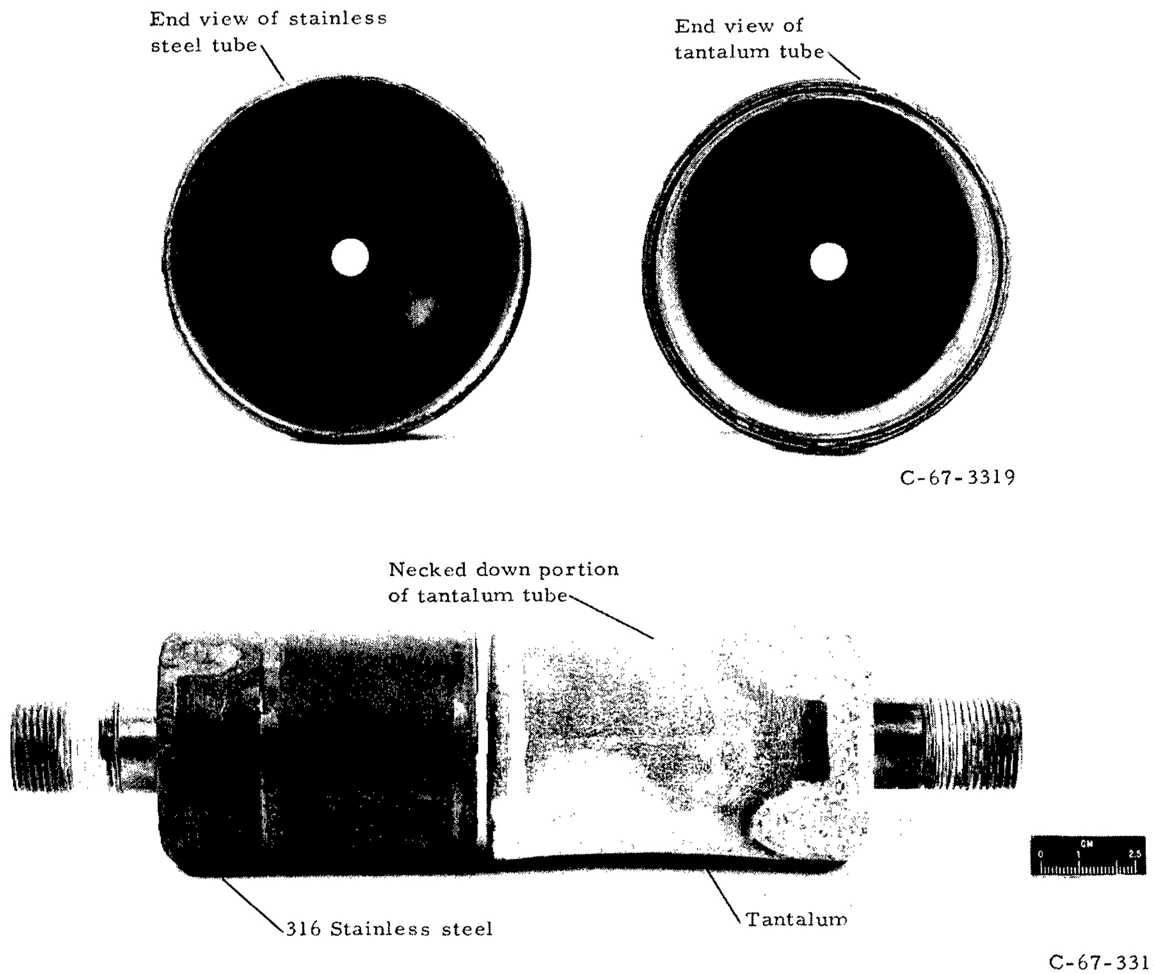
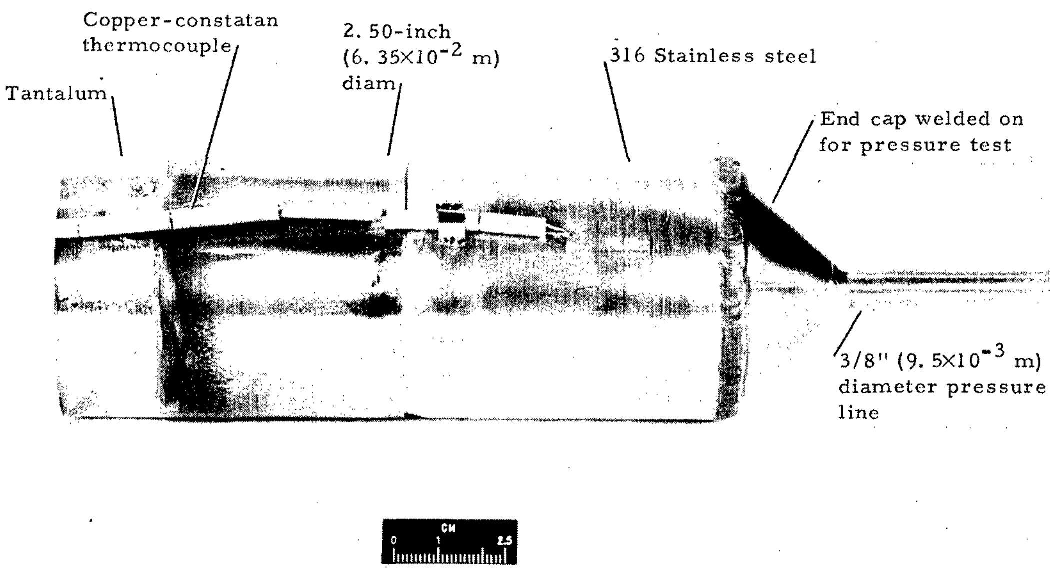


Figure 11. - 2.5-inch (6.35×10^{-2}-m) bimetallic tube after tensile test.



C-67-1692

Figure 12. - Bimetallic joint $2\frac{1}{2}$ inch diameter by 0. 125 wall-pressure test.

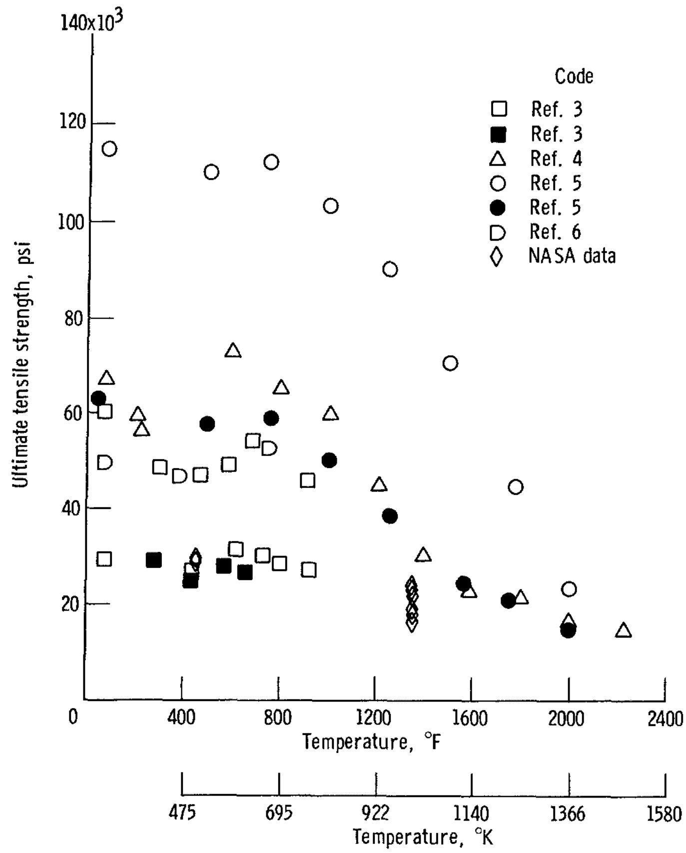


Figure 13. - Tensile properties of tantalum.

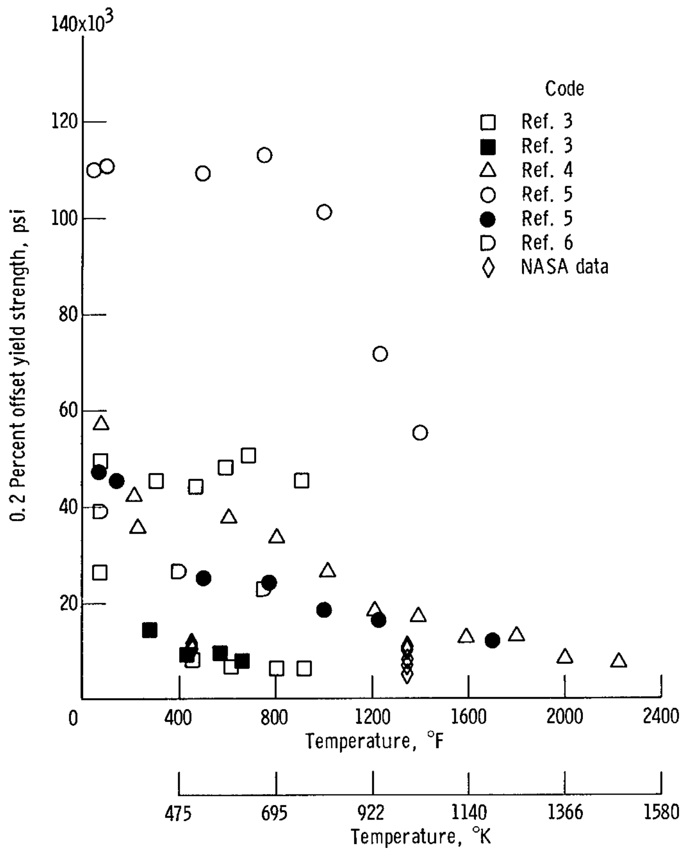


Figure 14. - Yield strength of tantalum.

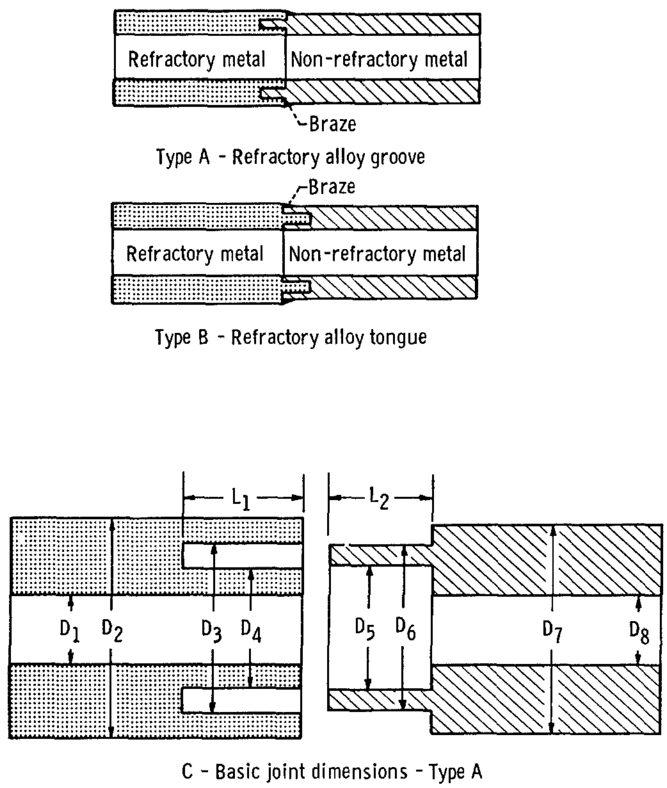


Figure 15. - Brazed bimetallic joint design.

NASA-Langley, 1968 —— 15 E-4218